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(54) **Title:** REGISTRATION OF TARGET OBJECT IMAGES TO STORED IMAGE DATA

(57) **Abstract:** A system for supporting frameless stereotactic surgery in which a plurality of two-dimensional images are acquired of a rigid surgical target immediately before the target is exposed surgically. The two-dimensional images are registered with both a reference coordinate system and with a previously acquired three-dimensional image of the target to provide a coordinate transformation from the reference coordinate system to the target. Even after the target is exposed surgically, the acquisition and registration of further two-dimensional images is continued, to keep the coordinate transformation up to date. Registration of the two-dimensional images to the reference coordinate system is facilitated by a tracker that is rigidly attached to the probe that is used to acquire the two-dimensional images. Preferably, one or more similar trackers are attached rigidly to the surgical target to enhance the updating of the coordinate system.

REGISTRATION OF TARGET OBJECT IMAGES TO STORED IMAGE DATA

Field and Background of the Invention

[001] The present invention relates to object-to-image registration, such as used in frameless stereotactic surgery and, more particularly, to a system and method for implementing object-to-image registration in which a three-dimensional preoperative image is registered to a local coordinate system of an operating room immediately prior to surgery.

[002] Stereotactic systems provide guidance to a surgeon based on preoperative tomographic images, such as images obtained with computerized tomography (CT), magnetic resonance imaging (MRI), nuclear medicine (NM) techniques or ultrasound. The first stereotactic systems, which were used for cranial surgery, were based on specially designed frames, called stereotactic frames, that were attached to the patient's head both during the preoperative image scan and during surgery. These frames have an inherent three-dimensional coordinate system, which is associated, through a coordinate transformation, with the preoperative image coordinate system. Based on the preoperative images, the surgeons select the target and the surgical path. The surgeons then refer to the coordinate system of the frame to perform the craniotomy and the surgery. Stereotactic frames provide high accuracy but have several disadvantages:

Stereotactic frames are bulky and interfere with the surgical procedure.

Surgical path planning and target localization in the stereotactic frame coordinates are time-consuming and tedious.

There is no real-time feedback on the preoperative images.

Stereotactic frames are invasive.

[003] With advances in sensing and computing technologies, a new generation of frameless stereotactic systems has been developed. These systems use a position sensor to interactively track the position and orientation of the surgical tool during the course of surgery. Interactive display of the preoperative images showing the location of the surgical tool provides the surgeon with real-time feedback. Frameless systems are easy to use compared to the frame-based systems. In addition, there is no bulky equipment involved.

[004] As a consequence of the elimination of the frame and its inherent three-dimensional coordinate system, a necessary step in frameless stereotactic surgery is the registration of the preoperative images to the local coordinate system in which the surgical tool is tracked. Consequently, frameless stereotactic surgery has been most extensively used in contexts in which this registration can be accomplished conveniently and accurately. In particular, in orthopedic surgery, the surgical target is one or more bones, which are mechanically rigid. One representative orthopedic procedure that has been effected in this manner is total hip replacement, as described by A.M. DiGioia et al. in "HipNav: pre-operative planning and intra-operative navigational guidance for acetabular implant placement in total hip replacement surgery," which is available on the Internet at http://ortho.cor.ssh.edu/projects/hipnav/paper.html. DiGioia et al. use an optical tracking system, specifically, the Optotrak™ optical tracking camera, available from Northern Digital Inc., Ontario, Canada, in conjunction with light emitting diodes (LEDs) mounted on the surgical tools, on bones such as the pelvis, and on the prosthetic (acetabular) implant. The preoperative image of the surgical target is a three-dimensional CT dataset. Registration of the CT dataset to the tracking coordinate system is accomplished by digitizing points on the bone surface, in the

local coordinate system, and matching those points mathematically to the imaged bone surface in the CT dataset. A similar registration procedure is described by Mittelstadt et al. in U.S. Patent No. 6,033,415.

[005] As noted above, DiGioia et al. use an optical tracking system. Other tracking systems are known, notably magnetic and electromagnetic tracking systems. Acker, in U.S. Patent No. 5,833,608 and U.S. Patent No. 5,928,248, and Acker et al., in U.S. Patent No. 5,558,091 and U.S. Patent No. 5,752,513 describe a system that uses static (DM) magnetic fields to track the position and orientation of a magnetic field sensor. Gilboa, in PCT Application WO98/36236, describes a system that uses (time-varying) electromagnetic fields to track the position and orientation of an electromagnetic field sensor.

[006] Obviously, the surgical target must be exposed in order for the surface of the surgical target to be digitized. Noninvasive imaging modalities also have been proposed, or used, for acquiring coordinates of the surface of the surgical target during surgery. Jerome Tonetti et al., "Percutaneous iliosacral screw placement using image guided techniques," *Clinical Orthopaedics and Related Research*, No. 354 pp. 103-110 (1998), experimented with ultrasonic imaging of the bone and soft tissue interface of the iliac wing of a cadaver pelvis. The Optotrak™ system was used to track the ultrasound probe. They acquired a set of points, in the intraperative reference coordinate system, that were registered to a CT image of this interface using Stealth™ software from Sofamor-Danek, Inc., of Memphis TN. Niko Pagoulatos et al., "Interactive 3-D registration of ultrasound and magnetic resonance images based on a magnetic position sensor," *IEEE Transactions on Information Technology in Biomedicine*, Vol. 3, No. 4, pp. 278-288 (1999) registered ultrasound images of a phantom with an MRI image of the phantom. The ultrasound scanner (Siemens

SONOLINE elegra) was tracked using a DC magnetic field tracking system (Flock of Birds 6DFOB, available from Ascension Technology Corp. of Burlington, VT). Leo Joskowicz et al., "FRACAS: a system for computer-aided image-guided long bone fracture surgery," *Journal of Computer-Aided Surgery*, Vol. 3, No. 6 (1999), registered fluoroscopic images of long bone fragments to a CT image of these fragments.

[007] Ultrasound imaging and fluoroscopy are noninvasive procedures that, in principle, could be effected prior to exposing the surgical target. Such imaging of the surgical target immediately prior to surgery would have several advantages, notably that the surgeon would not have to pause, after exposing the surgical target, to wait for the surgical target to be imaged. The desirability of such pre-surgical imaging and registration, and the lack of success heretofore in its actual implementation, also has been stated by Joskowicz et al. in the paper cited above:

> Image based registration is highly desirable since it does not require implanted fiducials or direct contact with the anatomy, which is not possible in a variety of closed and percutaneous procedures. Performing automatic, accurate 2D/3D anatomical registration is a challenging task which has yet to find a satisfactory solution.

Therefore, there is a widely recognized need for, and it would be highly advantageous to have, a method of frameless stereotactic surgery in which the preoperative image is registered to the local coordinate system, without first exposing the surgical target.

Summary of the Invention

[008] According to one embodiment of the present invention, an image registration system includes (a) a tracking system for locating a position and

orientation of a target relative to a reference coordinate system; (b) an imaging probe for acquiring two-dimensional images of the target; and (c) a processing system for registering the two-dimensional images to a reference coordinate system and for registering the first plurality of two-dimensional images to the three-dimensional image, thereby providing an initial coordinate transformation from the reference coordinate system to the three-dimensional image. One application of the system is for implementing frameless stereotactic surgery.

[009] The preoperative image that is to be registered to the local coordinate system, is referred to herein as a "three-dimensional image" because the modality, for example, CT or MRI, that is used to acquire the image produces a three-dimensional image volume of a portion of the patient that includes the surgical target. This image volume is made up of a plurality of three-dimensional image elements, or voxels, typically on the order of 2×10^7 voxels.

[0010] The images that are acquired immediately prior to surgery and that are used to register the three-dimensional image to the local coordinate system, are referred to herein as "two-dimensional images," because the modality, for example, ultrasound or fluoroscopy, that is used to acquire these images produces a set of two-dimensional image slices of the portion of the patient that includes the surgical target. Each image slice is made up of a plurality of two-dimensional image elements, or pixels, typically on the order of 2×10^5 pixels.

[0011] The local coordinate system, in which the surgical tool is tracked, is also referred to herein as the "reference coordinate system." The term "tracking," as used herein, refers to measuring, in real time, the position and orientation of an object relative to the reference coordinate system. To this end, in a preferred embodiment, one or more devices called "trackers" are attached to the surgical tool. The position

and orientation of the one or more trackers relative to the reference coordinate system are measured in real time by an associated tracking system. For example, if the tracking system is optical, the trackers are three or more LEDs; if the tracking system is magnetic, then the tracker is a three-component magnetic field sensor, and if the tracking system is electromagnetic, the tracker is a three-component electromagnetic field sensor.

[0012] According to embodiments of the present invention, the two-dimensional images are acquired while the surgical target is concealed, *i.e.*, before an incision is made that exposes the surgical target to view. One or more imaging tool trackers are rigidly attached to the imaging tool, for example an ultrasound probe, used to acquire the two-dimensional images. Each two-dimensional image is registered to the reference coordinate system by being acquired with the imaging tool at a particular position and orientation, relative to the reference coordinate system, as measured by the imaging tool tracker. This position and orientation determines the positions, relative to the reference coordinate system, of the points in the image, including, in particular, points in the image that correspond to points on the surface of the surgical target. In this way, a "cloud of points" on the surface of the target is digitized noninvasively. The two-dimensional images are registered to the three-dimensional image by matching this "cloud of points" to the surface of the target, as imaged in the three-dimensional image, by known methods, to produce a coordinate transformation from the reference coordinate system to the three-dimensional image. Subsequently, as the surgical tool is tracked by the tracking system, a representation of the surgical tool is displayed together with a representation of the surgical target, showing the true disposition, *i.e.*, the true position and orientation, of the surgical tool relative to the surgical target. Thus, an advantage of

the system is that a surgeon may perform surgery while looking at this display, without first exposing the surgical target.

[0013] After the two-dimensional images are acquired and registered to the three-dimensional image, the surgeon exposes the surgical target by cutting an appropriate incision in the patient. This incision, and subsequent surgical procedures, may cause the surgical target to move relative to the reference coordinate system, so the acquisition and registration of two-dimensional images is repeated as necessary to keep the coordinate transformation from the reference coordinate system to the three-dimensional image up to date. Alternately, the original set of two-dimensional images may be used for updating the position of the tool.

[0014] In accordance with one embodiment, while the surgical target is still concealed, one or more target trackers are attached rigidly to the surgical target in a minimally invasive manner, *i.e.*, without exposing the surgical target to view. For example, the target trackers may be inserted by injection prior to surgery. The target trackers are used to measure changes in the position and orientation of the surgical target, relative to the reference coordinate system, subsequent to the initial determination of the coordinate transformation from the reference coordinate system to the three-dimensional image. These measurements are also used to keep the coordinate transformation up to date.

[0015] As noted above, one or more surgical tool trackers are rigidly mounted on the surgical tool to enable tracking of the surgical tool. Most preferably, a surgical tool tracker is mounted at or near the tip of the surgical tool. Such a surgical tool, with a tracker mounted at or near its tip, is itself an aspect of the present invention.

Brief Description of the Drawings

[0016] The invention is herein described, by way of example only, with reference to the accompanying drawings, wherein:

[0017] FIGS. 1 and 2 are schematic depictions of noninvasive acquisition of two-dimensional image slices and registration of these image slices to a local coordinate system;

[0018] FIG. 3 shows two tracked ultrasound probes firmly secured to the leg of a patient;

[0019] FIG. 4 shows a surgical tool equipped with a tracker;

[0020] FIG. 5 is a simplified diagrammatic illustration of a system for registering a first plurality of two-dimensional images of a target object to a stored three-dimensional image of the target object;

Detailed Description of the Preferred Embodiments

[0021] The principles and operation of frameless stereotactic surgery according to the present invention may be better understood with reference to the drawings and the accompanying description.

[0022] Referring now to the drawings, Figure 1 shows, schematically, a patient 10 on a waterbed 12. The purpose of using waterbed 12 as a surgical platform is explained below. The surgical target inside patient 10 is a bone 14. A set of transverse ultrasound image slices of bone 14 and the surrounding tissue is acquired using an ultrasound probe 26.

[0023] The local coordinate system is defined by a magnetic tracking system 52 similar to the system described by Acker and by Acker et al. This system includes a magnetic field transmitter 16 underneath waterbed 12 and a multipurpose, computer

based control system 18. Insofar as control system 18 is part of the magnetic tracking system 52, control system 18 energizes transmitter 16 and receives consequent signals from various trackers, including a probe tracker 28 that is rigidly mounted on probe 26 and a pair of bone trackers 24 that are rigidly mounted on bone 14 as described below.

[0024] Input/output (I/O) means 22 is used to provide commands to control system 18, and also to input data to control system 18. In particular, I/O means 22 includes a suitable reader, typically a compact disk reader, for reading a previously acquired three-dimensional image of the portion of patient 10 that includes bone 14. A display device 20 is used to display this three-dimensional image in the conventional manner.

[0025] Figure 2 shows a transverse cross-section of patient 10 and waterbed 12 at the location of bone 14 and probe 26. Probe 26 is shown in two different angular positions relative to bone 14 to indicate that probe 26 is used to acquire many two-dimensional image slices of bone 14 and the surrounding tissue, as demarcated by the dashed lines. Preferably, probe 26 is moved automatically by a robotic system (not shown), under the control of control system 18, both in a transverse arc, as illustrated in Figure 2, and longitudinally parallel to bone 14, to continuously acquire two dimensional image slices of bone 14 and the surrounding tissue at many positions and orientations relative to the local coordinate system. As the image slices are acquired, points therein corresponding to the surface of bone 14 are identified by control system 18, using well-known edge detection techniques. Because probe 26 is tracked by control system 18, control system 18 can determine the coordinates of these surface points in the local coordinate system. When a sufficiently dense "cloud of points" has been acquired, control system 18 registers these points to the

three-dimensional image and derives a coordinate transformation that relates the three-dimensional image to the local coordinate system.

[0026] Probe 26 and the associated robotic system are mounted inside waterbed 12 to ensure a good acoustic impedance match between probe 26 and the soft tissues of patient 10. To this end, waterbed 30 is filled with degassed water. After the initial coordinate transformation between the local coordinate system to the three-dimensional image has been determined, control system 18 continues to move probe 26, to acquire more two-dimensional image slices, and to identify bone surface points in the new slices. The newly identified points are substituted for previously acquired points in the "cloud of points," to keep the "cloud of points" continuously updated. Control system 18 also periodically recomputes the registration of the "cloud of points" to the three-dimensional image, to keep the coordinate transformation up to date. Thus, the repeated scanning of bone 14 by probe 26 allows bone 14 to be tracked in real time.

[0027] The initial "cloud of points" also could be acquired manually, in the conventional manner, by placing probe 26 in contact with the skin of patient 10 at multiple locations near bone 14. The automatic data acquisition scheme described above has the advantage that the coordinate system is kept up to date despite movement of bone 14 subsequent to the initial determination of the coordinate system. The disadvantage of the automatic data acquisition scheme described above is the need for special means, such as waterbed 12, to maintain a good acoustic impedance match between probe 26 and the soft tissues of patient 10 despite the lack of direct contact between probe 26 and patient 10.

[0028] If the surgical target is only a portion of a long bone, then this disadvantage is overcome as illustrated in Figure 3. Two ultrasound probes 26' are

secured to a leg 11 of patient 10. Each probe 26' includes two orthogonal ultrasound sensors, for acquiring orthogonal images of the femur of patient 10. Rigidly attached to each probe 26' is a respective probe tracker 28'. Trackers 28' are used in conjunction with respective probes 26' in the same way as tracker 28 is used in conjunction with probe 26, to track probes 26'. Each probe 26' is firmly secured to leg 11 by a strap 42. During surgery on the upper portion of the femur, probes 26' continuously acquire "clouds of points" on the lower portion of the femur. Straps 42 maintain a good acoustic impedance match between probes 26' and leg 11, making waterbed 12 unnecessary in surgery on the upper portion of the femur.

[0029] Magnetic trackers 24, that are suitable for implantation on bone 14 in a minimally invasive manner, include the TetraLoc™ sensors available from Mednetix AG of Villigen, Switzerland. This sensor is less than one millimeter in diameter, and so can be attached to a screw. The screw in turn is attached to a thin screwdriver. The screw and the screwdriver are pushed through the skin and the soft tissue of patient 10 to bone 14 at a place where the surface of bone 14 is near the skin of patient 10. For example, if bone 14 is a pelvis, a suitable location for implanting tracker 24 is the iliac wing. The screw is screwed to bone 14 and the screwdriver is withdrawn, leaving a small incision, less than two millimeters wide, through which bone 24 is not visibly exposed. Alternatively, the additional trackers may be attached by injection with a needle or other minimally invasive injection means prior to the surgery.

[0030] The location on bone 14 where the tracker 24 is implanted (e.g., injected) cannot be specified in advance with sufficient accuracy to use the location of tracker 24, as determined by the tracking system 52, as one of the points in the "cloud of points." Nevertheless, because tracker 24 is rigidly attached to bone 14, any *change* in the position or orientation of tracker 24, subsequent to the implantation of

tracker 24, reflects an identical change in the position and orientation of bone 14. By way of example, individual trackers may be attached to each of two parts of a hip joint prior to dislodging it during surgery to give their required relative orientation.

[0031] The continuously monitored positions and orientations of trackers 24 are used, along with the continuously updated "cloud of points," to keep up-to-date the coordinate transformation that relates the three-dimensional image to the local coordinate system. Algorithms, notably, predictor-corrector algorithms such as Kalman filters, for accomplishing this are known in the art and need not be recited here.

[0032] Magnetic trackers less than one millimeter in diameter also are suitable for use as probe tracker 28, and as trackers for a surgical tool. Figure 4 shows one such surgical tool, a scalpel 32. Conventionally, trackers, such as the LEDs of optical tracking systems, have been mounted rigidly on a tool such as scalpel 32 on handle 38 thereof. A magnetic tracker such as the TetraLoc™ sensor is small enough to be mounted, as a tool tracker 34, at or near tip 40 of blade 36 of scalpel 32. The datum of true interest to the surgeon, which the surgeon wants to see on display device 20, is the disposition of tip 40 relative to surgical target 14. The closer the tracker 34 is to tip 40, the more accurately does the image displayed on display device 20 reflect the true disposition of tip 40 relative to surgical target 14.

[0033] Referring to FIG. 5, in accordance with the present invention, a registration system 50 is provided for registering a first plurality of two-dimensional images of a target object to a stored three-dimensional image 56 of the target object. In the registration system 50, an ultrasound probe 60 acquires a set of transverse ultrasound image slices of a target object, and sends this information to processing system 54. Simultaneously, a probe tracker (not shown) rigidly attached to the

ultrasound probe 60 sends signals to the processing system 54, which are used to identify the position and orientation of the probe tracker relative to a reference coordinate system. The processing system 54, which may be software or firmware based, registers the transverse ultrasound image slices of the target object to the reference coordinate system and registers the transverse ultrasound image slices of the target object to a stored three-dimensional image 56. The registration system 50 also includes a tool 62' for manipulating the target object, wherein an additional probe tracker (not shown) is fixed relative to the tool 62. Subsequently, display 58 shows a representation of tool 62, displayed together with a representation of the target object, as the tracking system 52 tracks tool 62. This provides a true position and orientation of tool 62 relative to the target object. The tool 62 may be used to manipulate the target object while looking at display 58. For example, the tool may be a surgical instrument.

[0034] Though it is not necessary to this embodiment of the registration system 50, it may be desirable to acquire a second plurality of two-dimensional images using ultrasound probe 60 after in order to update the coordinate transformation between the reference coordinate system and stored three-dimensional image 56 after the initial transformation. Alternately, the original set of two-dimensional images may be used to update the coordinate transformation between the reference coordinate system and stored three-dimensional image after the initial transformation.

[0035] Though it is not necessary to this embodiment of the registration system 50, ultrasound probe 60 may be rigidly fixed to the target object to maintain a good acoustic impedance match between probe 60 and the target object,

particularly when employing the scheme described above of updating the coordinate transformation.

[0036] Although a primary application of the present invention is to surgery, such as performed on human or animal patients, it will be appreciated that the present invention also is applicable to other uses where registration of an object in a real-time reference coordinate system to stored images of the same object.

[0037] While the invention has been described with respect to a limited number of embodiments, it will be appreciated that many variations, modifications and other applications of the invention may be made.

What is Claimed is:

1. A system for registering a first plurality of two-dimensional images of a target object to a stored three-dimensional image of the target object, comprising:

a tracking system for locating a position and orientation of a first tracker relative to a reference coordinate system;

an imaging probe for acquiring the first plurality of two-dimensional images while the target object is positioned within the reference coordinate system, wherein the first tracker is fixed relative to the probe; and

a processing system configured for registering the two-dimensional images to the reference coordinate system and registering the first plurality of two-dimensional images to the stored three-dimensional image.

2. The system of claim 1, wherein the processing system is software based.

3. The system of claim 1, wherein the processing system is further configured for registering a second plurality of two-dimensional images acquired by the imaging probe of the target object to the reference coordinate system and for registering the second plurality of two-dimensional images to the stored three-dimensional image to provide an updated coordinate transform from the reference coordinate system to the stored three-dimensional image.

4. The system of claim 1, wherein the stored three-dimensional image is acquired using an imaging modality selected from the group consisting of computer tomography, nuclear medicine, MRI or ultrasound.

5. The system of claim 1, wherein the imaging probe is an ultrasound probe.

6. The system of claim 1, wherein the first tracker is rigidly attached to the imaging probe and wherein the tracking system is configured to track the first tracker with respect to the reference coordinate system while simultaneously acquiring the two-dimensional images.

7. The system of claim 1, further comprising:

a second tracker fixed to the target object, wherein the processing system is further configured for correcting an initial coordinate transformation based on the position and orientation of the second tracker over time.

8. The system of claim 7, wherein the target object is in a body, and wherein the second tracker is fixed to the target object by injection.

9. The system of claim 1, further comprising:

a tool for manipulating the target object with reference to the stored three-dimensional image.

10. The system of claim 9, wherein the first tracker is in a fixed position with respect to the tool, further comprising:

a display device for displaying a representation of the stored three-dimensional image along with a representation of the tool, the representations being mutually disposed in a manner that reflects a mutual disposition of the tool and the target object.

11. The system of claim 10, wherein the tool includes a tip and wherein the first tracker is attached to the tool proximate the tip.

12. The system of claim 10, wherein the tool includes a tip and wherein the first tracker is rigidly attached to the tip.

13. The system of any of the above claims 1-12, wherein the first tracker is optical.

14. The system of any of the above claims 1-12, wherein the first tracker is magnetic.

15. The system of any of the above claims 1-12, wherein the first tracker is electromagnetic.

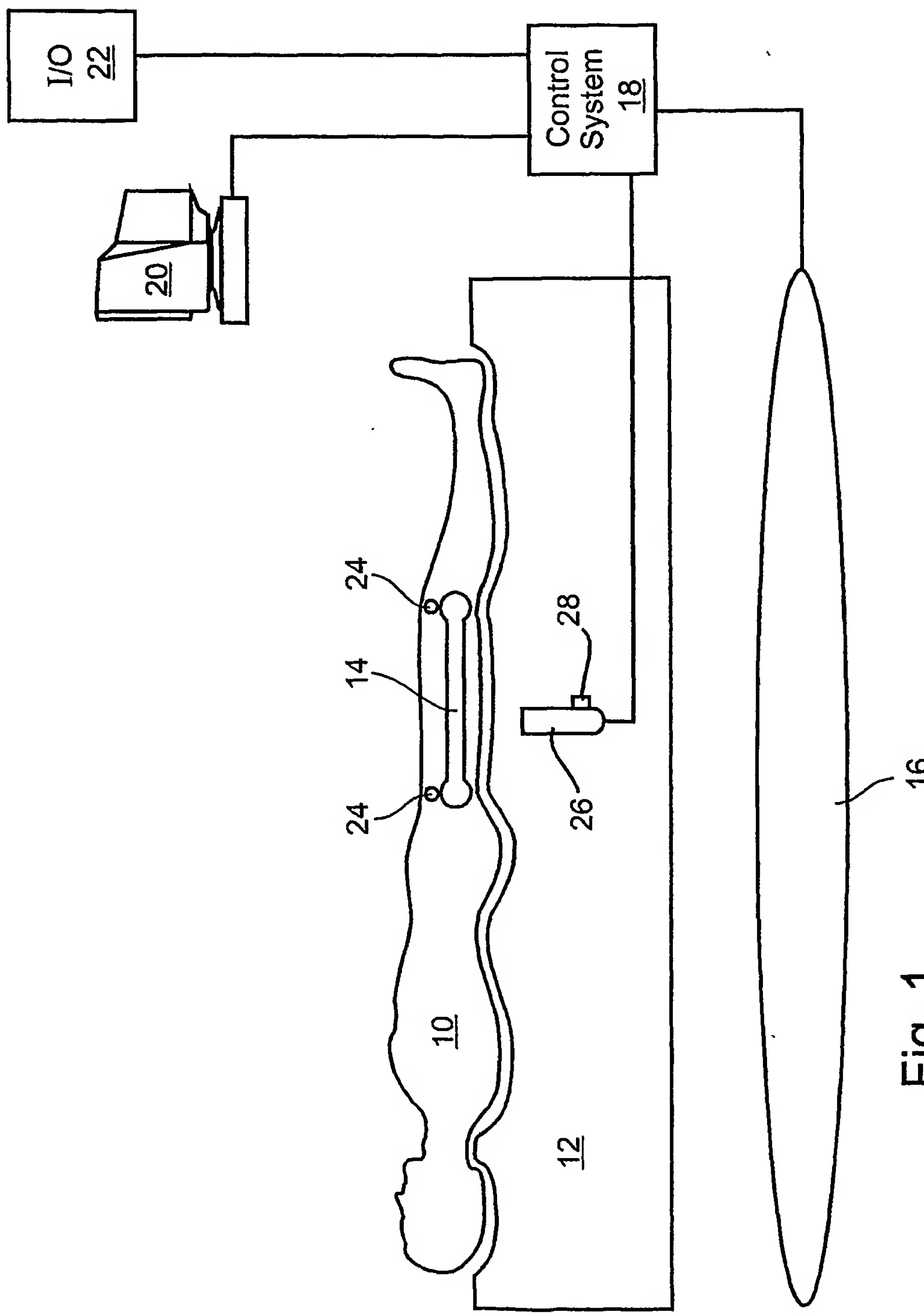


Fig. 1

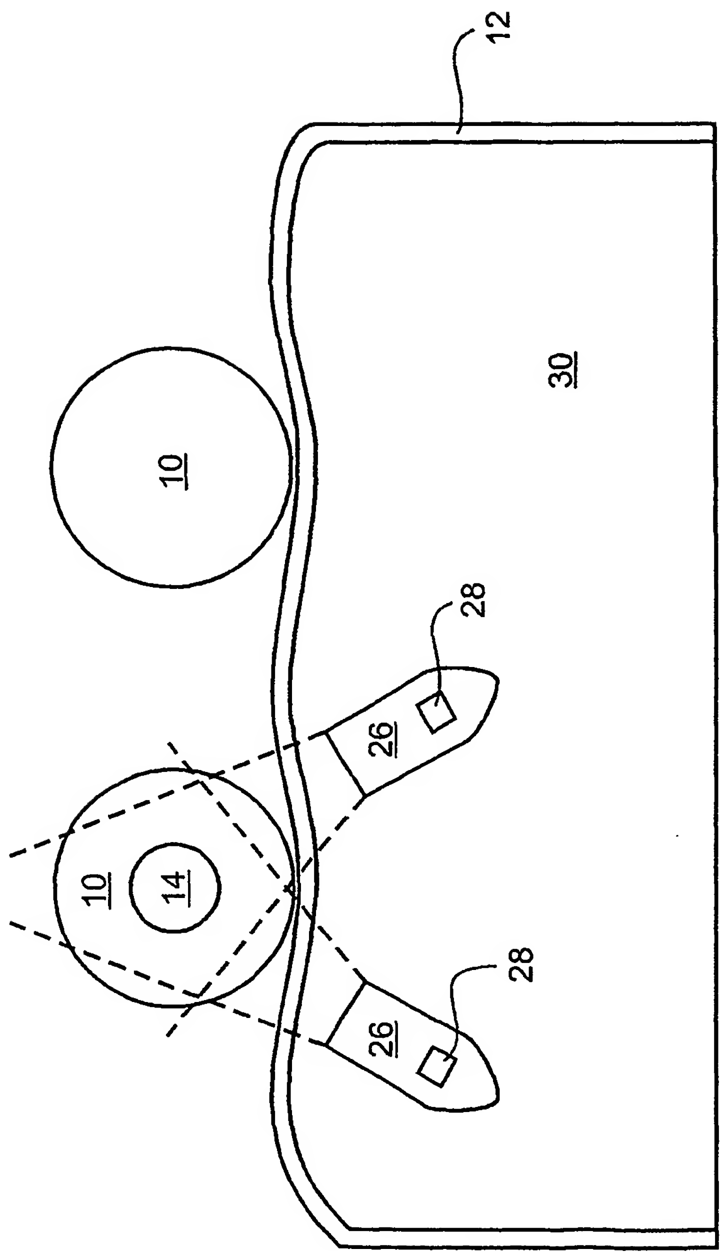


Fig. 2

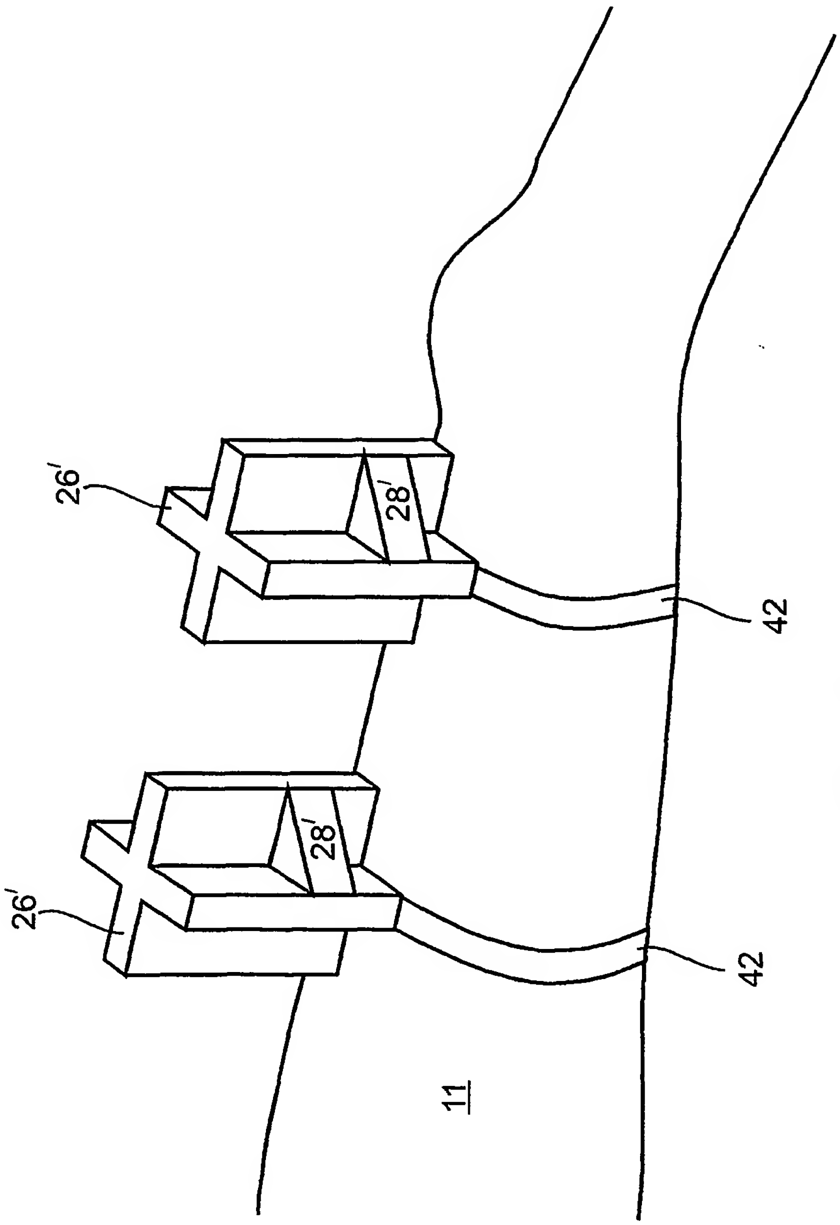


Fig. 3

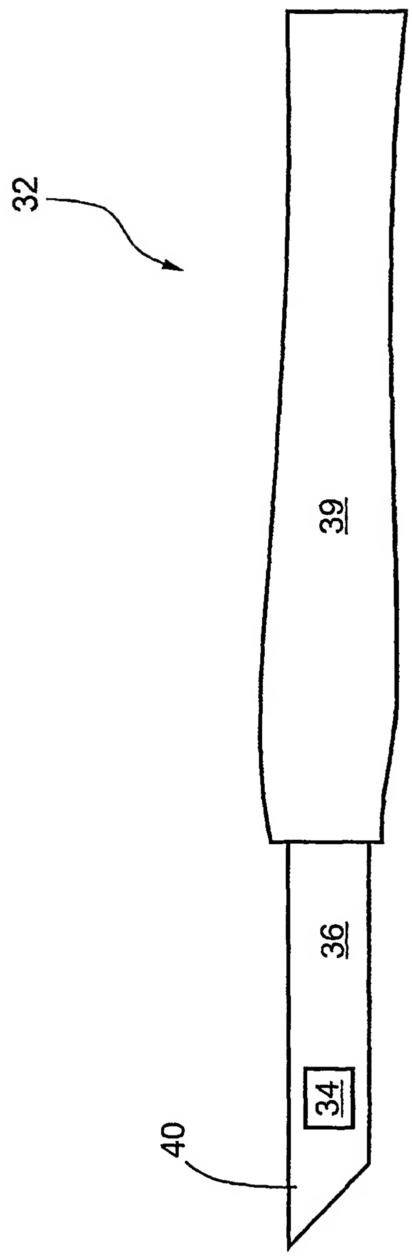
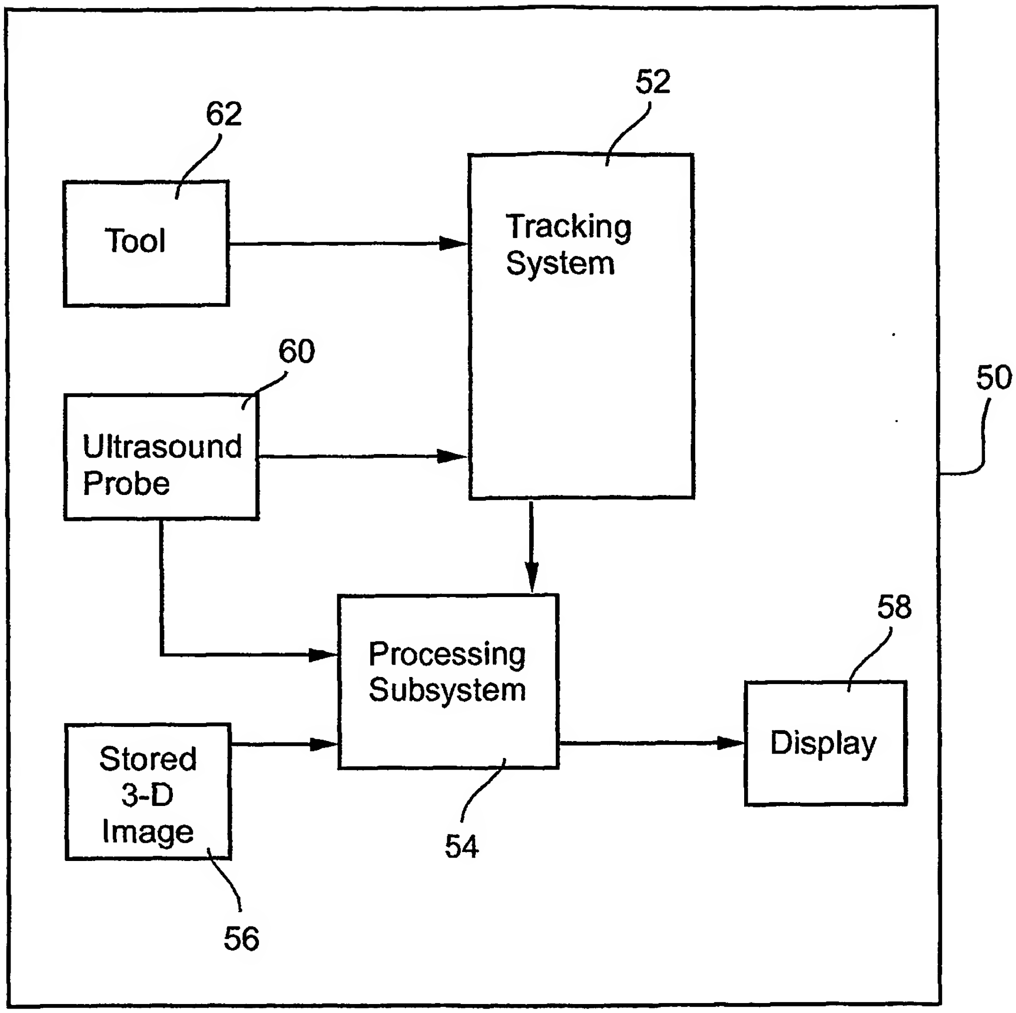


Fig. 4



62
52
Tool
Tracking System
60
50
Ultrasound Probe
58
Processing Subsystem
Stored 3-D Image
Display
54
56

Fig. 5